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An Efficient Self-Organizing Node Deployment Algorithm for Mobile Sensor Networks

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Abstract—Wireless Sensor Networks (WSNs) constitute the platform for a broad range of applications such as those related to national security, surveillance, military, health care, and environmental monitoring. Maximising coverage using the resource constrained nodes is usually a goal to provide the expected quality of service for these applications. This problem has been studied extensively in recent years, especially when the connectivity and energy efficiency are of high significance. In this paper, we propose a new distributed move-assisted algorithm, called SODA, to efficiently provide the maximum coverage for WSNs with self-organising mobile nodes. SODA is based on a deployment algorithm recently reported in the literature which is inspired by the equilibrium of molecules. However, while SODA's transition from chaos to order is faster, the final coverage provided by SODA is also insensitive to the initial deployment of the nodes and no certain level of coverage during the initial deployment is required. This is achieved by detecting the local network density and adjusting the partial force applied at each step in each neighbourhood accordingly. Our extensive simulation study shows the advantages of SODA including lower power consumption, faster and more effective coverage.

Index Terms—coverage, distributed wireless sensor network, energy efficiency, node deployment

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are being used in many different applications in the world, particularly with the proliferation of Micro-Electro-Mechanical Systems (MEMS) technology which has promoted the development of smart sensors [1]. These applications vary from entertainment, travel, retail, and industry to medicine, and emergency management [2].

In WSNs, providing the adequate coverage is a fundamental problem that has gained much attention recently [3] within the aim to provide the maximum sensing coverage over the Region of Interest (ROI). The required coverage can be achieved by accurate deployment of sensors after the initial deployment. Therefore, random deployment of mobile sensors does not guaranty the expected coverage in the ROI.

The mobile sensor deployment algorithms in WSN is classified as centralised or distributed [4]. The distributed method is fault tolerance, scalable, and cost-efficient and, hence a more popular method in wireless sensor networks [5], [6]. Distributed deployment of sensors does not rely on a centralised node, i.e. sink, to decide on all the sensors movements. In the distributed strategy, every sensor can communicate with its neighbouring nodes to decide about its movement at each step. The communication method, the data sent and received,

and also the communication and sensing range are some of the essential parameters to be specified in every distributed deployment algorithm.

In different algorithms, different methods are used for communication between neighbouring nodes to increase the coverage in the area [6]–[11]. Some algorithms are inspired by observing some natural phenomenon behaviours to cope with the distributed sensor network requirements. For example, neighbourhood movement theory that is seen in the animal aggregation movements, like birds migration, is applied in a deployment algorithm proposed in [12]. In this deployment algorithm [12], sensors move based on the average of the neighbour's positions and as a result, create a uniform sensor placement to achieve the required coverage. In another study [13], an algorithm is proposed for a distributed sensor network that the equilibrium of molecules inspires sensor movement. This algorithm can provide full coverage after a rather high number of steps and subject to providing a somewhat high initial coverage percentage over initial deployment. Another deployment algorithm using a clustering approach to achieve better power usage and coverage has also been proposed in [13] with the same concept for sensor movements. However, none of them considers the assumptions which are applicable in the real scenarios. This includes the initial deployment of sensors in many applications that the environment could be antagonistic in which manual deployment of sensors might not be possible. For instance, a sensor network could be deployed near the crater of a volcano to measure temperature, pressure, and seismic activities [14] or security surveillance in military operations [5]. Therefore, the initial deployment of sensor nodes with a certain percentage of initial coverage is not always possible.

In this paper, we aim to develop a distributed deployment algorithm, called SODA for mobile sensor networks. Our primary goal is to achieve maximum coverage within an acceptable range of energy consumption and time cost. The Self-Organizing Deployment Algorithm (SODA) is based on the Distributed Self-Spreading Algorithm (DSSA) [13] which is inspired by the equilibrium of molecules. SODA addresses the DSSA limitations such as sensitivity to the minimum percentage of initial deployment coverage, the long transition time from chaos situation to order, and limitations in providing the appropriate coverage for single-point-deployment scenarios, where all nodes are initially located over a single sub-area such as one corner or at the centre of the area. The superiority

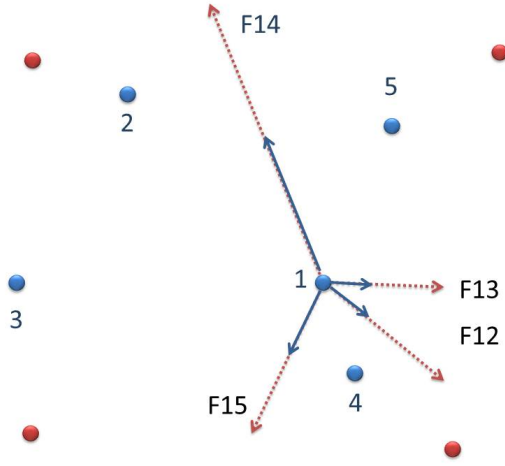


Fig. 1: Partial forces in between sensor 1 and its neighbours.

of SODA is due to the adjustment of partial force where the network is dense locally.

The rest of the paper is organised as follows. Section II presents an introduction to DSSA followed by the SODA solution in Section III. The performance evaluation section to describe the simulation specification and results is under Section IV while our conclusions are drawn in Section V.

II. A BRIEF REVIEWING OF DSSA

The DSSA is inspired by the equilibrium of molecules, which balances the energy of the particles to remain in their locations. This balance is caused by particles which stay in their lowest energy point with an almost the same space with each other in a distributed manner. Similarly, optimal spacing in between sensors create the required coverage.

In DSSA, it is assumed that a number of sensors are randomly distributed in an area. Sensors can communicate with each other if they are located within their communication range, called C_R , and can sense their environment with the sensing range, S_R . The communication between sensors are performed in order to find their neighbouring nodes and to exchange the requisite information. The collected information is then used to decide about the appropriate location of each node to provide the required coverage for the area. The DSSA executed at each node after an initial step.

In the initial step of the DSSA, the communication range, C_R and sensing range, S_R values are given which dependent on sensors' specifications that are the same for all the sensors. The initial location of sensors is specified in 2D vector (p_0). The higher dimension for sensor locations is possible by adding another component to location vector. The *threshold1* and *threshold2* are two parameters that can check the exit points of the algorithm and should be defined in the initial step, which are explained later on. Another important variable is \mathcal{M} which is the expected density in the sensor network. Expected density is the average number of sensors in a one-hop neighbourhood. Expected density is calculated by $\mathcal{M} = (\frac{N \cdot \pi \cdot C_R^2}{A})$ where C_R is communication range, S_R is

sensing range, N is the number of sensors, and A is the size of the ROI. In addition to expected density, D represents the local one-hop neighbourhood density of every sensor. The expected density and local density control the movement of the sensors.

The central core of DSSA is the partial force that moves the sensors. This force is dependent on the current location of sensors, the distance in between every two neighbouring sensors, and the local density. Local density and partial force have a direct relationship that is the same as the movement of particles in physics which follow Coulomb's Law.

The partial force at step n for sensor and its neighbouring sensor is a repulsive force calculated as:

$$f(i, j) = \frac{D^i}{\mathcal{M}^2} (C_R - |p_n^i - p_n^j|) \frac{p_n^j - p_n^i}{|p_n^j - p_n^i|} \quad (1)$$

p_n^i stands for the position of sensor i at step of n , and D^i stands for the local density of sensor i at step of n . As appears in Equation (1), the magnitude of partial force depends on the position of the nodes. If any neighbours of the sensor, like sensor j , has greater value in one dimension then the magnitude of that force is positive and negative otherwise.

For every sensor node, the total force that moves that sensor is the cumulative force of all neighbouring nodes in its one-hop neighbourhood. The movement is independent of the movement of any other sensor node inside or outside of the neighbourhood. This process is executed as long as the condition for stopping the algorithm is not satisfied. These conditions are:

- **Oscillation Check:** The execution of the algorithm at each node is stopped when it reaches its oscillation limit. Oscillation happens when a sensor moves back and forth between almost the same locations consecutively. The number of oscillation is counted by oscillation count, O_{count} . The distance that a sensor moves back and forth is called *threshold1*, and oscillation limit, O_{lim} , is the maximum number of oscillation that a sensor can take before it stops its movement. A sensor stops its movement, if its O_{count} equals the O_{lim} .
- **Stability Check:** If a sensor moves less than a *threshold2* over a number of steps, it can be concluded that it is reached its stable position and it can stop its movement. To count the number of these steps, a variable, Stability Limit, S_{lim} , is defined. The stability check is useful if a sensor breaks down or has reached a stable status.

III. SELF-ORGANIZING DEPLOYMENT ALGORITHM (SODA)

A. DSSA limitations

The concept of partial force and the background idea of equilibrium of molecules, make DSSA a prominent solution in WSN to achieve full coverage. However, many assumptions in DSSA are not feasible. Sensitivity to the minimum percentage of initial coverage, initial uniformity, non-single-point-deployment are some assumptions in DSSA which cannot be applicable in the realistic scenarios. In addition to these

Algorithm 1 SODA algorithm

```
1: procedure INITIALIZE
2:    $P \leftarrow$  an array includes all the sensors locations
3:    $C_R \leftarrow$  communication range of sensors
4:    $S_R \leftarrow$  sensing range of sensors
5:    $D \leftarrow$  calculated local density
6:    $\mathcal{M} \leftarrow$  calculated expected density
7: end procedure

8: procedure SODA(Until all the sensor nodes are stable)
9:   Calculate local density for the sensor
10:  if Sensor  $i$  is not stable then
11:    if Local density  $>$  Expected Density ( $\mathcal{M}$ ) then
12:      Partial Force is  $\leftarrow F_{new_n}(i, j)$ 
13:    else
14:      Partial Force is  $\leftarrow f_n(i, j)$ 
15:    end if
16:    Update next step position for the sensor
17:    Check for oscillation
18:    if Oscillation happens then
19:      Increase  $O_{count}$ 
20:      if  $O_{count} > O_{limit}$  then
21:        Move the sensor to centroid of
        oscillation points and make it stable
22:      end if
23:    end if
24:    Check for stability
25:    if Sensor node is stable then
26:      Increase  $S_{count}$ 
27:      if  $S_{count} > S_{limit}$  then
28:        make the sensor stable
29:      end if
30:    end if
31:  end if
32: end procedure
```

assumptions, the high order of time for DSSA from chaos to order state has been observed as one of the challenges. These assumptions and challenges in DSSA are:

1) *Single-point-deployment*: In many applications in sensor networks like chemical sensitive environment or borders, single-point-deployment is the only way initially locate sensors since uniformly locating of sensors are not feasible. In DSSA, the initial deployment of sensors are considered to be uniformly distributed in the ROI where in some environments, locating sensors randomly across the entire area is not possible. Therefore, single-point-deployment is a necessity in most of applications which initially causes a high local density in a part of ROI.

The partial force in DSSA depends on the local density and distance in between sensors. An illustration of a sensor node and its neighbours in the DSSA is shown in Figure 1. The blue forces are for a scenario where sensor 1 and 4 blue sensors

in neighbourhood are in the area and the red forces are for a scenario that 4 more red sensors are added in the area. The size of the partial forces have a direct relationship with their distance to the sensor 1 and the local density. Therefore, the partial force for a closer sensor like sensor 4, F_{14} , is greater than, partial force for sensor 2, F_{12} . In another scenario, if the local density of a sensor increases by adding some sensors, red sensors, the value of the partial forces even for previous sensors increase, shown as red forces.

For scenarios where the density is quite high is a sub-region, the high force moves all the sensors with an unreasonable intensity to the corners. The $\frac{D}{\mathcal{M}^2}$ shows the density factor in the partial force. The $\frac{D}{\mathcal{M}^2}$ parameter is large when sensor i is surrounded with many sensor neighbours. On the other hand, in the dense areas ($C_R - |p_n^i - p_n^j|$) affects the partial force inversely. The adjacent sensor node creates a larger force in comparison to sensor which is far apart and not in the dense area. Therefore, the intense move is caused by $\frac{D}{\mathcal{M}^2}$ known as density factor, which is large in this case, and also the small distance between sensors which cause ($C_R - |p_n^i - p_n^j|$) parameter to be closer to C_R . Addressing this issue can improve the performance of the deployment algorithm for all scenarios including the single-point-deployment cases.

2) *Sensitivity to minimum percentage of initial coverage*: In order to achieve the best coverage, a minimum coverage during the initial deployment is required in DSSA. The random deployment of the sensors using enough number of sensors in most cases provide more than 90% initial coverage of the ROI [13]. Obtaining a high percentage coverage during the initial deployment is unreasonable as this level of uniformity for the initial deployment is impossible for most of realistic applications. Therefore, we aim to address this issue.

3) *A long process from chaos to order state*: In DSSA, the partial force is the key concept. The partial force in a single-point-deployment is large at the few first steps of the algorithm, which causes a chaos in the system. The chaos situation proceed to a stable state as the affect of partial force decrease by lower partial force. Although after the chaos situation, sensors can move, they do not move within long distance. In DSSA algorithm the order state happens in the last steps of the algorithm before the full coverage is achieved. Therefore, the DSSA needs a long time to reach the stable state.

B. Self-Organizing Deployment Algorithm (SODA)

Self-Organizing Deployment Algorithm (SODA) is proposed to overcome the above-mentioned limitations in DSSA. All those limitations are in fact originated from the DSSA uniformly treating of any local area regardless of the density of each neighbourhood. Whereas, the partial force should depend on th density of each neighbourhood to adjust the intensity of applied partial forces for different circumstances. The number of sensors and expected density are two parameters that should determine the intensity of the applied partial force. Adjusting the applied force during the first few movements of each sensor is especially of high significance to avoid moving

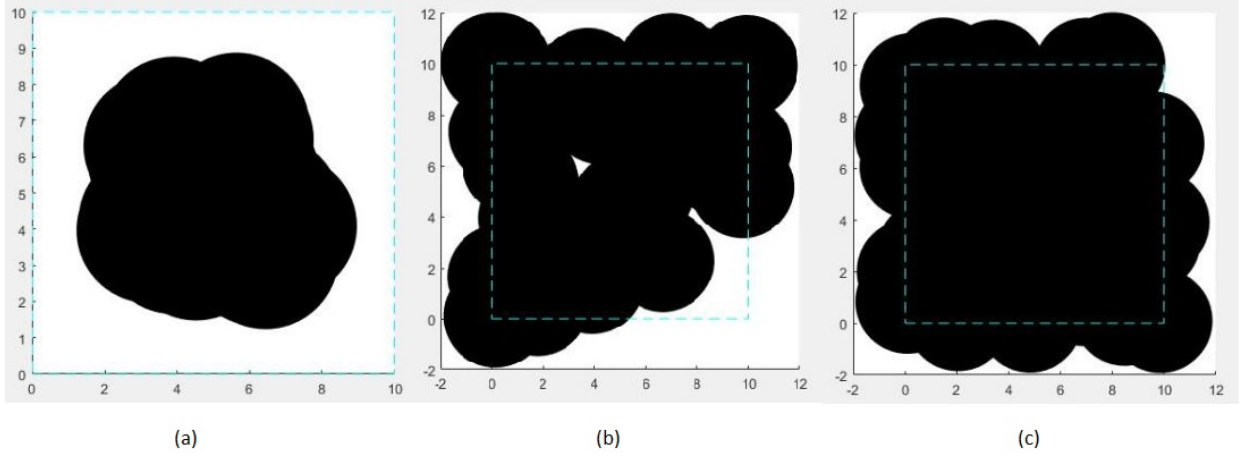


Fig. 2: Covered area in a 10x10 region, 30 sensor nodes, $C_R = 4$ and $S_R = 2$: (a) Initial deployment. (b) Final coverage by DSSA. (c) Final coverage by SODA.

nodes chaotically. The partial force is stateless and has no information about the previous and next layout. Therefore, the number of sensors in the neighbourhood and the expected density at the end of the algorithm, are used as a guidance to control partial force to behave as it is expected.

The detail of this algorithm is presented in Algorithm 1. In SODA, two steps are considered: initialization step and force calculation step. The SODA initiate its process by initialising the P , C_R , S_R , D , and calculating M which is the expected density. After initialisation, SODA is executed at each node as long as the node is unstable. An unstable node is defined as a node in which its travelled distance over a certain number of consecutive movements is less than a certain value or a node which is oscillating between a pair of points more than a certain number of times.

The partial force at each node is calculated based on the local density at each neighbourhood. Equation 1 is used when the local density is lower than the expected density. The following equation is used otherwise:

$$F_{new_n}(i, j) = \frac{D}{M \times N} (C_R - |p_n^i - p_n^j|) \frac{p_n^j - p_n^i}{|p_n^j - p_n^i|} \quad (2)$$

where the applied force is reduced for dense neighbourhood. In this equation D , M , and N are local density, expected density, and number of neighbours, respectively. C_R stands for communication range and p shows the positions of the sensors.

IV. PERFORMANCE EVALUATION

A. Simulation Specification

The DSSA and SODA algorithms are simulated in a 10 x 10 region using Matlab. The C_R and S_R are assumed 4 and 2 respectively. The *threshold* for oscillation and stability is considered to be 0.1522, the same as those used in DSSA performance study [13]. The sensor nodes are considered to be randomly distributed around a point which is chosen randomly in the region of interest. The initial coverage for each scenario

is different as the deployment point is chosen randomly. The final coverage by running DSSA in one scenario with the initial coverage presented in Figure 2(b), where this algorithm covers 97.2% of the area. These results are based on 30 sensor nodes, $C_R = 4$ and $S_R = 2$ in a 10 x 10 area. In this deployment, the whole coverage of the requested area is not achieved. The final coverage by SODA for the same initial deployment is presented in Figure 2(c). The initial coverage of 40.76% , presented in Figure 2(a), has resulted in a full coverage by SODA.

The final coverage and the mean travelled distance by every sensor are measured for different number of deployed sensors in two areas: a 10 x 10 small area and another 20 x 20 area. To obtain reliable results, every experiment is repeatedly executed for each chosen deployment point a number of times and the average results are taken. In the experiments with the 20 x 20 size, the value of *threshold* for oscillation and stability is considered to be half of the one for small area, which is 0.0761. This is because the *threshold* should be smaller in the larger area as the same size sensor needs more accurate movement in the larger area to be able to cover the area more efficiently.

B. Results

1) *Area Coverage*: The initial covered area and the final coverage of DSSA and SODA algorithms are shown in Figures 3 and 4, respectively. The initial coverage for both algorithms are the same because the initial deployment in both experiments are identical. As expected, the final coverage area provided by each algorithm is increased by increasing the network size (i.e. number of sensors). However, the result from the figures shows an improvement in the covered area obtained by SODA compared to those of DSSA in both scenarios. This difference decreases as the number of sensors increases. Therefore, the improvement in coverage descends as the number of sensors increase. It is applicable in both scenarios. In SODA a dense initial deployment can be locally recognised and very close sensors can be separated gradually

regardless of the initial percentage of the coverage. Therefore, the 10% increase in the coverage provided by SODA in sparse scenarios and when the network is not crowded by sensors is achieved. The effectiveness of SODA in larger networks are more noticeable. As can be seen from Figure 4, SODA continuously performs well and is able to achieve up to 20% higher coverage than that of DSSA in an area of 20 x 20.

2) *Mean distance*: Figures 5 and 6 show the mean distance travelled by each node in both DSSA and SODA. The total distance travelled by each node before reaching stable state is not appropriate for comparison. Therefore, the mean distance is calculated to compare DSSA and SODA from this angle. This distance is important in case of power usage, and movement mobility of every sensor which at last causes network stability. Figures 5 and 6, show that the SODA has smaller mean distance and in result use less power generally in both areas. The correct movement of the sensors in SODA, decreases the transition time from chaos to order state in compare to DSSA algorithm. The applied partial force in SODA is more appropriate, because of the consideration of the local density and sensor numbers. The proper movement causes the sensors to reach their steady state sooner.

The behaviour in Figures 5 and 6 show that by increasing the number of sensors the mean distance that each sensor travels, rises and very slowly decreases after a while. In Figure 7, three different number of sensors are simulated in the SODA algorithm, and this image is captured after three runs. Based on Figures 5 and 6, the mean distance that every sensor travels increase as the number of sensors increases and then decreases after a while. The turning point in Figure 6, for instance, is 110 sensors. The result of the simulation in Figure 7 shows 6.52, 7.36, and 6.53 as mean distance of 150, 115, and 80 sensors respectively. This data confirm the result from Figures 5 and 6.

The theoretical reason behind this behaviour is the distribution of the sensors. In any size of the area, the mean distance of each sensor node increases as the number of sensor increases, because the applied partial force for each node increases and it makes sensors to move more. However, this increment stops after a certain point which is called Optimal Number of Sensor (ONS). The ONS is where the full coverage of an area is achieved. Although before ONS point the mean distance of sensors increases, after this point the reduction in mean distance is seen. This behaviour is also based on density of sensors after this point. The number of neighbours for each sensor increases as the total number of sensors increases. The distribution of these neighbours is asymmetric before ONS point, and it makes partial force to be large, however, when the number of sensors is greater than the ONS, the node arrangement in each neighbourhood tends to be more symmetrical and, hence, their forces counterbalance each other. Consequently, less force implied less movement which results in lower mean distance.

V. CONCLUSION

Coverage can be considered as the effectiveness measurement of wireless sensor network due to its direct impact on the

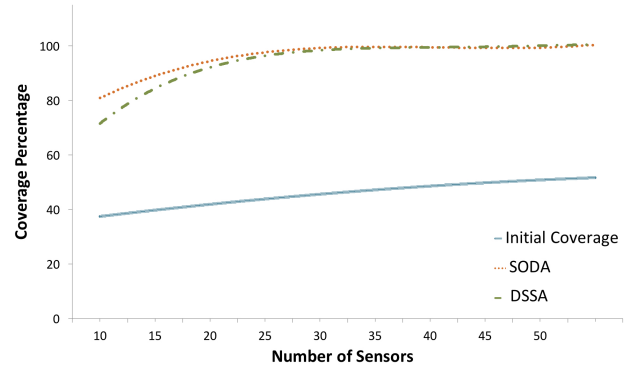


Fig. 3: The area coverage in 10 x 10 region

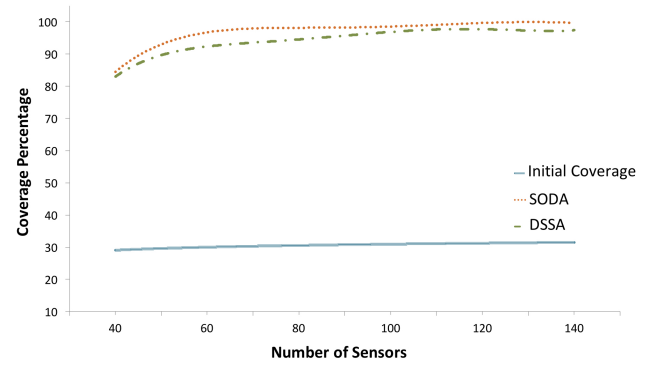


Fig. 4: The area coverage in 20 x 20 region

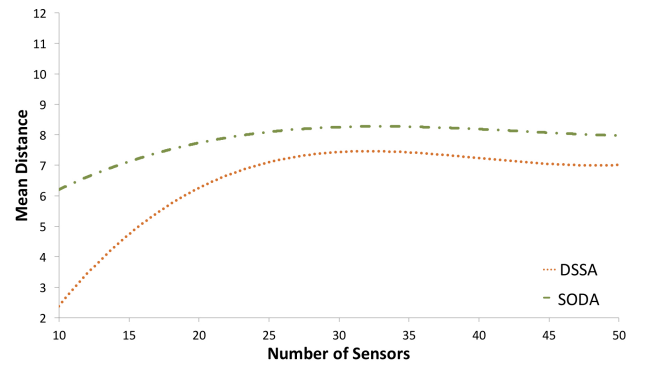


Fig. 5: Mean distance in 10 x 10 region

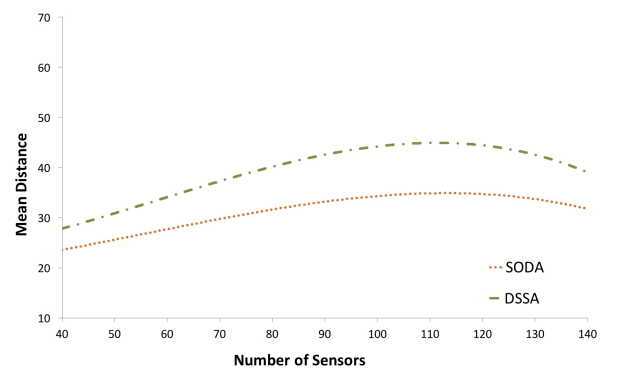


Fig. 6: Mean distance in 20 x 20 region

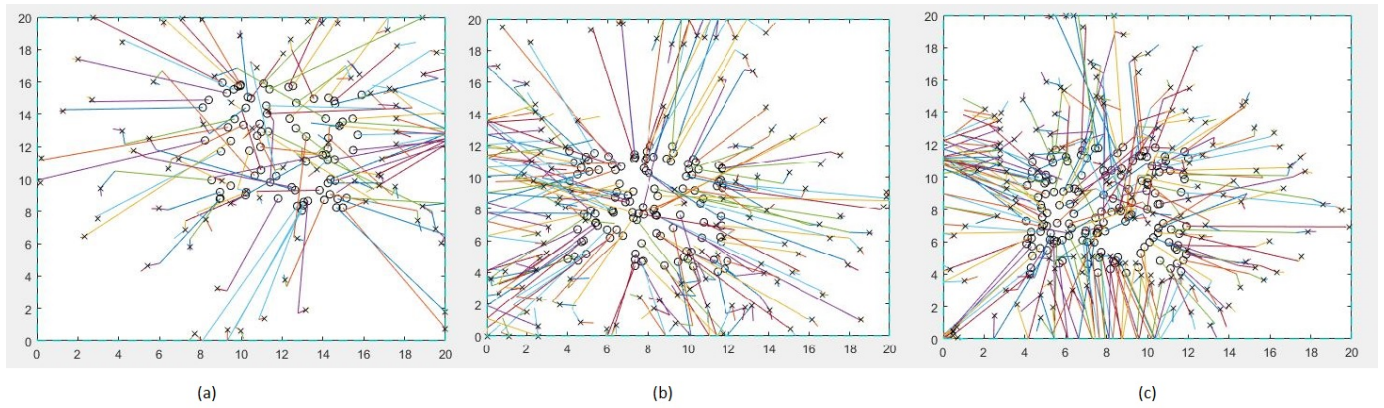


Fig. 7: Sensors movements in 20x20 region: (a) Movements of 80 sensors. (b) Movements of 115 sensors. (c) Movements of 150 sensors.

network performance. Many factors such as sensors technical specifications, network topology and most importantly, deployment algorithms influence the designated coverage. Maximizing coverage using the resource constrained nodes is usually the goal of any deployment algorithm.

In this paper, we have proposed a Self-Organizing Deployment Algorithm (SODA) for mobile sensor networks. SODA is based on the DSSA algorithm reported in the literature, which is inspired by the equilibrium of molecules to provide the required coverage. However, the effectiveness of DSSA is highly dependent on the initial deployment of the nodes and also subject to providing a minimum initial coverage. These issues have been addressed in SODA. Furthermore, SODA transition from chaos (i.e. initial deployment) to order (stabilised nodes) states is faster.

In our performance study, performance of SODA has been compared against that of DSSA by simulating both algorithms in Matlab, and measuring the final percentage of the coverage, and the mean distance travelled by every node. Simulation results confirm the advantages of SODA to achieve a more uniform distribution of nodes after applying the algorithm and hence a better coverage. The SODA solution has improved the final percentage of coverage by 10% and the mean distance has been reduced by 10% to even 60% in compare to those of DSSA. The faster transition from chaos to order causes achieving the faster symmetric form of each neighbourhood within less mean distance for every sensor and consequently resulting in lower power consumption.

In more realistic scenarios, WSNs can be used in a large area, where the ROI can be divided into multiple sub-region for easy deployment. Finding an optimal solution to provide a trade-off between the number of sub-region and the designated coverage can be a direction for future work. Additionally, extending SODA to be able to utilise two-hops neighbouring information, or even more, when calculating the partial force at each neighbourhood may yield benefits beyond those of one-hop SODA. As another line, we are going to study this in the future.

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